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RESULTS OF EXPERIMENTAL CORRELATION OF MODEL AND FULL SCALE HELICOPTER AND VTOL LONGITUDINAL DYNAMICS

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FOREWORD

The research in this report was conducted by the Department of Aeronautical Engineering of Princeton University under the sponsorship of the United States Army Transportation Research Command, as Phase 1 of work under the ALART Program. The development of the apparatus and a part of the experiments reported herein were conducted under the Office of Naval Research Contract Nonr-1858(11).

The work was performed under the supervision of Professor A. A. Nikolsky, Department of Aeronautical Engineering, Princeton University.

Mr. Esteban Martinez was responsible for the design and development of the apparatus. Mr. Theodor Dukes developed the electronic circuitry.

This work was administered for the United States Army by Mr. John Yeates.

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SUMMARY

Results of experiments to evaluate the degree to which dynamically similar models tested in the Princeton University Forward Flight Facility simulate the dynamics of full scale aircraft are presented. Two models were utilized, a single rotor helicopter and a tilt-wing VTOL aircraft. Excellent agreement between the response of the models and the full scale aircraft was obtained.

INTRODUCTION

The Princeton University Forward Flight Facility is a unique apparatus designed specifically to measure directly dynamic characteristics of aircraft at low speeds. The equivalent full scale speed range encompassed by the apparatus depends upon the particular model, i.e., the scale factor, but roughly extends from hovering to 50 kts. for large scale models and to 100 kts. for small scale models. The two primary objectives of experiments on this apparatus are:

1.) To determine the dynamic behavior of proposed full scale aircraft by means of dynamically similar scale models.

2.) Through fundamental experimental investigations of stability and control problems at low speeds, to develop methods of analysis with the ultimate goal that the prediction of the dynamics of helicopters and VTOL aircraft can be developed to the state that exists with respect to conventional aircraft.

It is with the former of these two objectives that the tests considered herein are concerned.

Numerous difficulties arise in the testing of full scale aircraft in the low speed flight regime. The most important of these are:

1.) Helicopters and VTOL aircraft are usually dynamically unstable in this speed range making stick fixed response experiments difficult and dangerous.

2.) At slow forward speeds full scale testing is very sensitive to gusts and air turbulence. For example, at a forward speed of 40 kts., a 6 ft/sec. vertical gust causes an angle of attack change of approximately 5° resulting in normal accelerations of the order of $\frac{1}{10}$ g for a typical single rotor helicopter.

3.) Many instrumentation difficulties arise due to the high vibration level usually present in these aircraft and in measuring flight velocities near hovering.

However, it is obvious that unless a considerable number of quantitative experiments are performed in this speed range where prediction of aerodynamic forces is exceedingly difficult, if not impossible, the dynamics of these aircraft cannot be predicted with any confidence and there is little possibility of improvement in the handling qualities of aircraft at low speeds. At the present time, the lack of experimental data makes even the prediction of the forces produced by an isolated rotor in this speed range questionable.

Thus the development of a facility to provide quantitative data under carefully controlled conditions on the dynamic behavior of aircraft at low speeds was considered highly desirable. At Princeton University a facility was constructed to accomplish this objective. It is completely described in reference 1.

Dynamically similar models are flown in unrestrained flight in the plane described by the vertical and the heading of the model. The model can move with respect to the carriage a limited distance ($\pm$ 6 inches horizontally and $\pm$ 2 inches vertically) in this plane without being influenced by the presence of the carriage. This relative motion, the <u>displacement</u> of the model with respect to the carriage is the driving signal (error signal) for the positioning servomechanisms that determine the motion of the carriage. The performance of the servomechanism make the carriage capable of following any reasonable motions of a model. Thus the free motions of the model completely determine the motion of the carriage and accurate measurements of the motion of the model along the track are made during the period of time in which the relative displacement between the model and the carriage is less than the above limits. One servomechanism drives the entire carriage in response to the horizontal motions of the model, and another drives the horizontal tapered tube up and down with respect to the carriage to follow altitude changes of the model. The apparatus is shown in figure 1. It should be noted that this apparatus is entirely distinct from a wind tunnel and provides quantitative data that cannot be obtained in a wind tunnel or for that matter in any other apparatus in existence.

As with any new apparatus it is desirable to determine how well the results of experiments with models compare with full scale data such that the dynamics of the aircraft can be inferred directly from the model results. It is the purpose of this report to discuss such comparisons obtained from two widely different configurations. The comparisons of the experiments with theory will be considered in detail in later reports.

RESULTS

A. Correlation of Single Rotor Helicopter Response

A dynamically similar model of the Sikorsky H-19D was constructed for the explicit purpose of correlating model response data with full scale. The model is a $\frac{1}{6.625}$ scale model shown in figure 1 mounted on the servo carriage. The comparison of the equivalent full scale parameters of the model and the full scale machine are shown in Table I. A detailed description of the model will be found in reference 2. There was some difficulty in obtaining data satisfactory for correlation from the full scale aircraft. Flight test data was available from four programs on the H-19D at a minimum flight speed of about 40 kts (advance ratio .11). Below this flight speed the dynamics tend to deteriorate rapidly and it is not possible for the pilot to maintain the stick fixed for a sufficient period of time to obtain a response useful for correlation purposes. This limitation is, of course, not present in evaluating dynamics from models in the Facility and thus in these cases much more information on the dynamics can be obtained from a model.

The data available on the full scale helicopter mentioned above had such a wide scatter (the period varied by as much as a factor of two) that it was not useable. Therefore, Princeton undertook further flight test experiments through the cooperation of the U.S. Army. About three days were available for installation of equipment and experimentation. Stick fixed responses were measured on the full scale helicopter at one trim speed, to determine the response of the full scale machine and the repeatability of the full scale response. Two of these responses are shown in figures 4a and 4b. The particular item of significance to note in these responses is that after the initial input the pilot was moving the stick a small amount at the approximate frequency of the long period motion thus damping the response. It is probably this same phenomena, inherent in most pilots that caused wide scatter in the other response data, the pilot providing an effective feedback. The influence of the pilot is particularly noticeable in this helicopter at this flight condition since the true stick fixed motion is approximately neutrally stable as shown by the model responses. The influence of the stick motion of the pilot would not have been so noticeable if the response had been well damped or markedly unstable.

Model responses at this equivalent flight speed were measured for forward and backward pulse inputs. Experimental results are presented in figure 3. The results converted as measured to full scale values are shown in figures 5a and 5b. A large number of responses were measured on the track and the repeatability of the data was excellent.

Due to the influence of the pilot's stick movements on the full scale transient motion it was necessary to use an analog computer as an intermediate step to obtain direct correlation between the model data and the full scale data. An analog computer was therefore used to determine the response of the model to the full scale input. The detailed procedure was as follows:

1.) The equations of motion of the helicopter were set up on an analog computer and the stability derivatives adjusted so that the computed response to a pulse input was the best possible simulation of the experimentally measured model response to an identical input.

2.) Then, with <u>no changes</u> in the computer set-up, the measured full scale input was applied to the computer. The resulting response will be a good representatiion of the model response to the input measured in the full scale experiments. Thus, the purpose of the computer was only to determine the response of the model to the rather irregular input obtained in the flight test.

3.) The correlation between the model response and the full scale response is demonstrated by a comparison of the computer solution and the experimentally measured full scale response.

The computer responses are shown in figures 6, 7a and 7b. Figures 8a and 8b are an overlay of the computer predicted response of the model to the flight test input compared to the experimental results of the flight test. The comparison is indeed remarkable in all respects. The magnitudes of the variable output, the period and damping, and the initial response all agree very well. Thus it can be seen that the model provides an excellent simulation of the full scale dynamics.

A later report will discuss in detail the analysis of the model dynamics and the theoretical prediction of the motion.

B. <u>Correlation of Tilt-Wing VTOL Response</u>

Typical results of transient response correlation experiments on the $\frac{1}{5.2}$ scale model of the VERTOL 76 (VZ-2) are presented in figures 9a through 9d. A photograph of this model appears as figure 2. A comparison of the scaled up physical characteristics along with those of the full scale machine is presented in Table I. The model responses are to be compared to similar responses measured on the full scale aircraft in tests conducted by the NASA at Langley Field, Va. and presented in figures 10a through 10c.

All model variables have been converted as measured to their full scale equivalents determined by the model scale factor as discussed in reference 2. Full scale information is presented directly as recorded from copies of oscillograph traces with the exception of pitch attitude which was not measured directly but obtained by integrating the pitch rate record.

The general purpose of transient response testing is to determine period, damping, variable magnitudes and overall response characteristics of the particular machine under observation. With these points in mind it is reasonable to compare the full scale and model responses on the basis of these particular characteristics.

In figures 9a through 10c the peak to peak time intervals of the oscillations are evaluated for the various variables measured and the average results indicate that both the model and the full scale exhibit periods between 4.4 and 4.8 seconds. This agreement is also reflected in the variations in peak to peak intervals exhibited by both the model and full scale. These variations in period are possibly attributable to non-linearities arising from wing and tail local flow conditions.

General character and damping agreement is demonstrated best in the overlays of model and full scale responses presented in figure 11. It can be seen that both the model and full scale exhibit slight convergences, the envelopes of which are essentially identical. Presence of unknown initial conditions and input pulse return overshoot in the full scale responses are typical of the vagaries to be expected in full scale data, and make a direct magnitude comparison difficult, but the general character of the oscillation is preserved and is well simulated by the model responses.

CONCLUSIONS

On the basis of comparisons presented herein of the dynamic responses of low-speed aircraft models and their full scale counterparts, it can be concluded that the dynamic characteristics of full scale aircraft can be accurately simulated by dynamically similar models tested under controlled conditions in the Forward Flight Facility. In particular, the ability to duplicate the dynamic characteristics of a single rotor helicopter and a tilt-wing VTOL with models has been demonstrated.

Results obtained from correlation of two such widely different configurations at conditions of marginal stability, allow one to conclude that accurate simulation of most conceivable types of low-speed aircraft can be accomplished by the use of dynamically similar models. Such a capability is of real significance in a flight regime where flight testing is extremely difficult and somewhat hazardous, and where existing methods of prediction are distressingly crude and inaccurate.

REFERENCES

1. Martinez, E., A New Facility for the Study of Aircraft Dynamics., Princeton University, Aeronautical Engineering Department, Report No. 532, April 1961.

2. Bennett, R. M., and Curtiss, H. C., Jr., An Experimental Invesitgation of Helicopter Stability Characteristics near Hovering Flight using a Dynamically Similar Model., Princeton University, Aeronautical Engineering Department, Report No. 517, July 1960.

TABLE I

TRIM CONDITIONS AND PHYSICAL CHARACTERISTICS

General layout and model blade and hub characteristics are essentially identical to those of full scale machines.

H-19D

	Model	Full Scale
Gross weight	7730 pounds	7450 pounds
I_{yy}	12000 slug-feet^2	11,600 slug-feet^2 (approx.)
V_{trim}	39.6 knots	41 knots
Rotor speed	204 RPM	206 RPM
μ	0.118	0.12
Center of gravity location	130.5 (Sta.)	130.5 (Sta.)

V-76

Gross weight	3350 pounds	3400 - 3450 pounds
I_{yy}	2620 slug-feet^2	2600 slug-feet^2
V_{trim}	43.2 knots	42 knots (approx.)
Rotor speed	1425 RPM	1410 RPM
$\frac{\mu}{\cos iw}$	0.103	0.1 (approx.)
Center of gravity location	33.1% m.a.c.	33.7% m.a.c. (approx.)
	11.2 inches below wing pivot	12.2 inches below wing pivot (approx.)

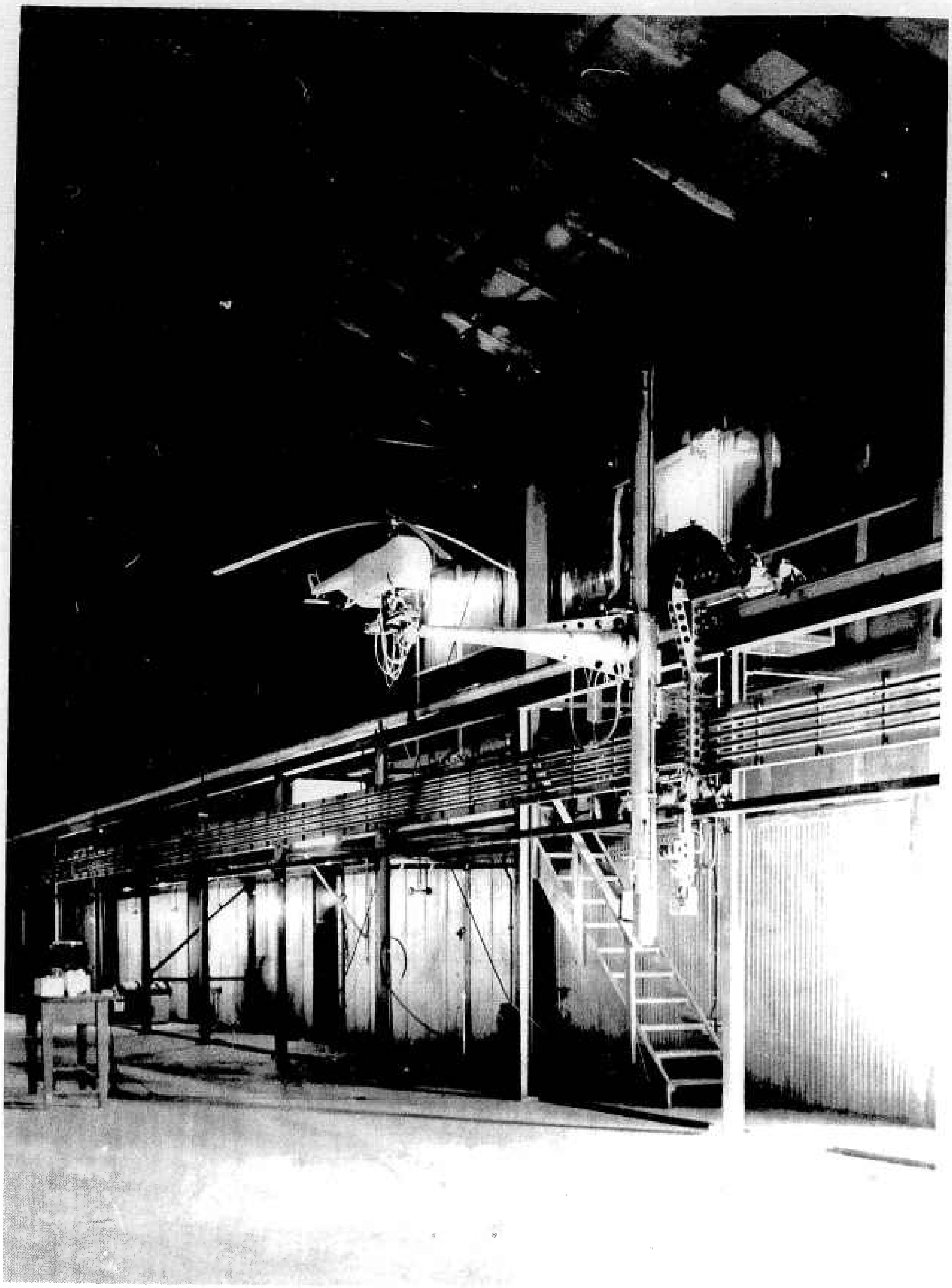

Fig. 1: H-19D Model on Servo Carriage

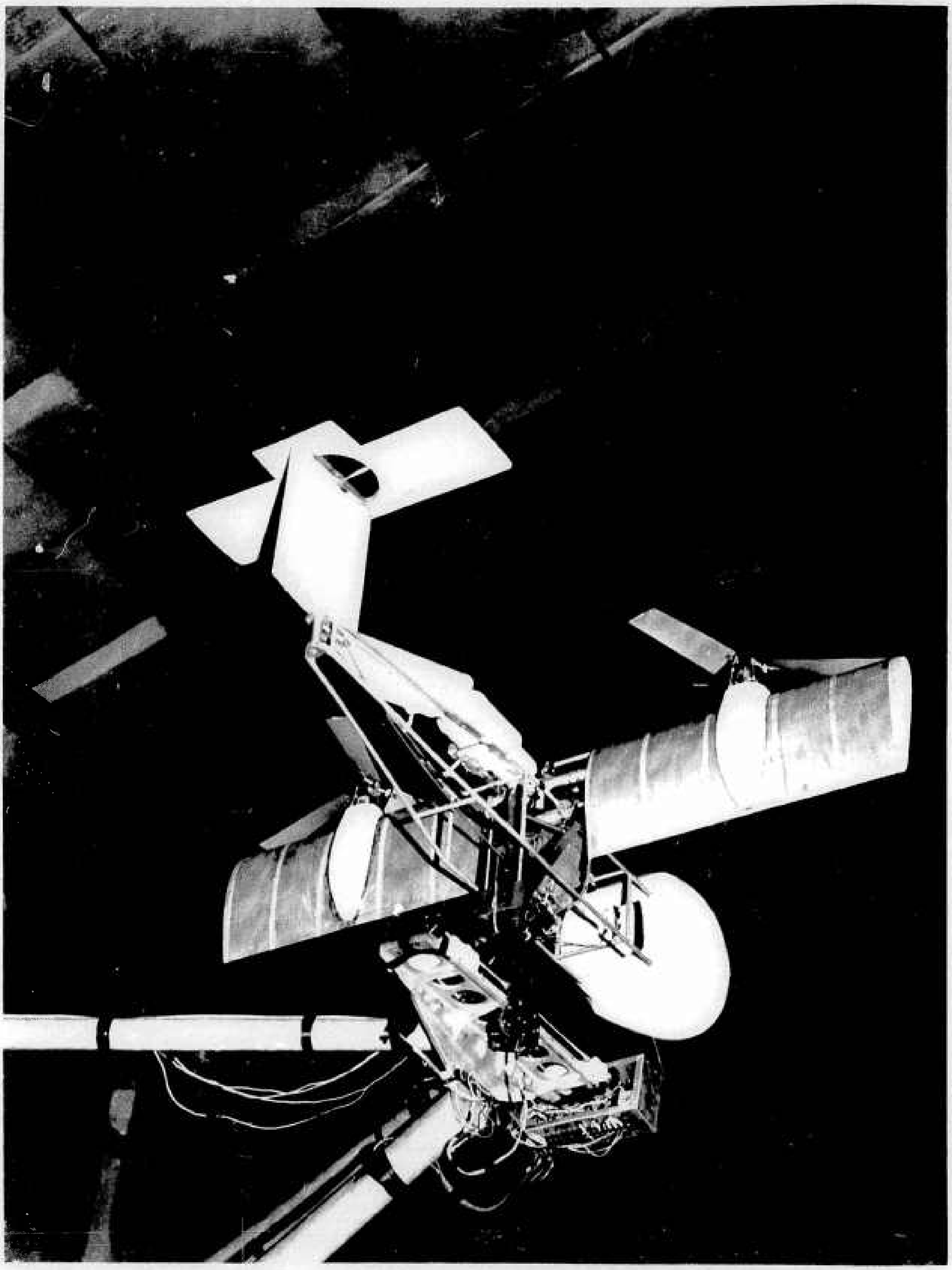

Fig. 2: V-76 Model

TYPICAL TRANSIENT RESPONSE OF HELICOPTER MODEL

ABOUT FORWARD FLIGHT TRIM CONDITION

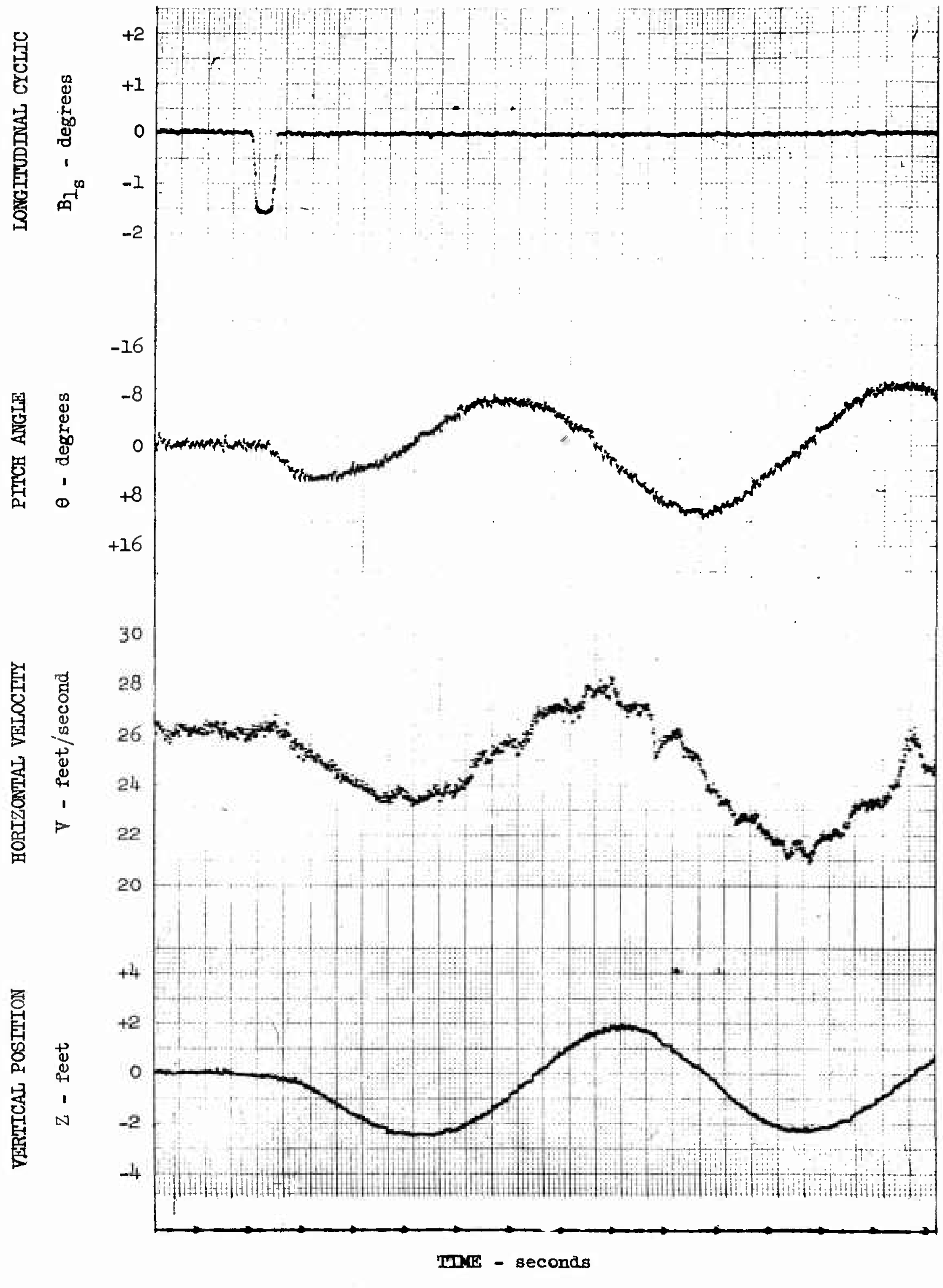

Fig. 3: H-19D: Representative Facility Data

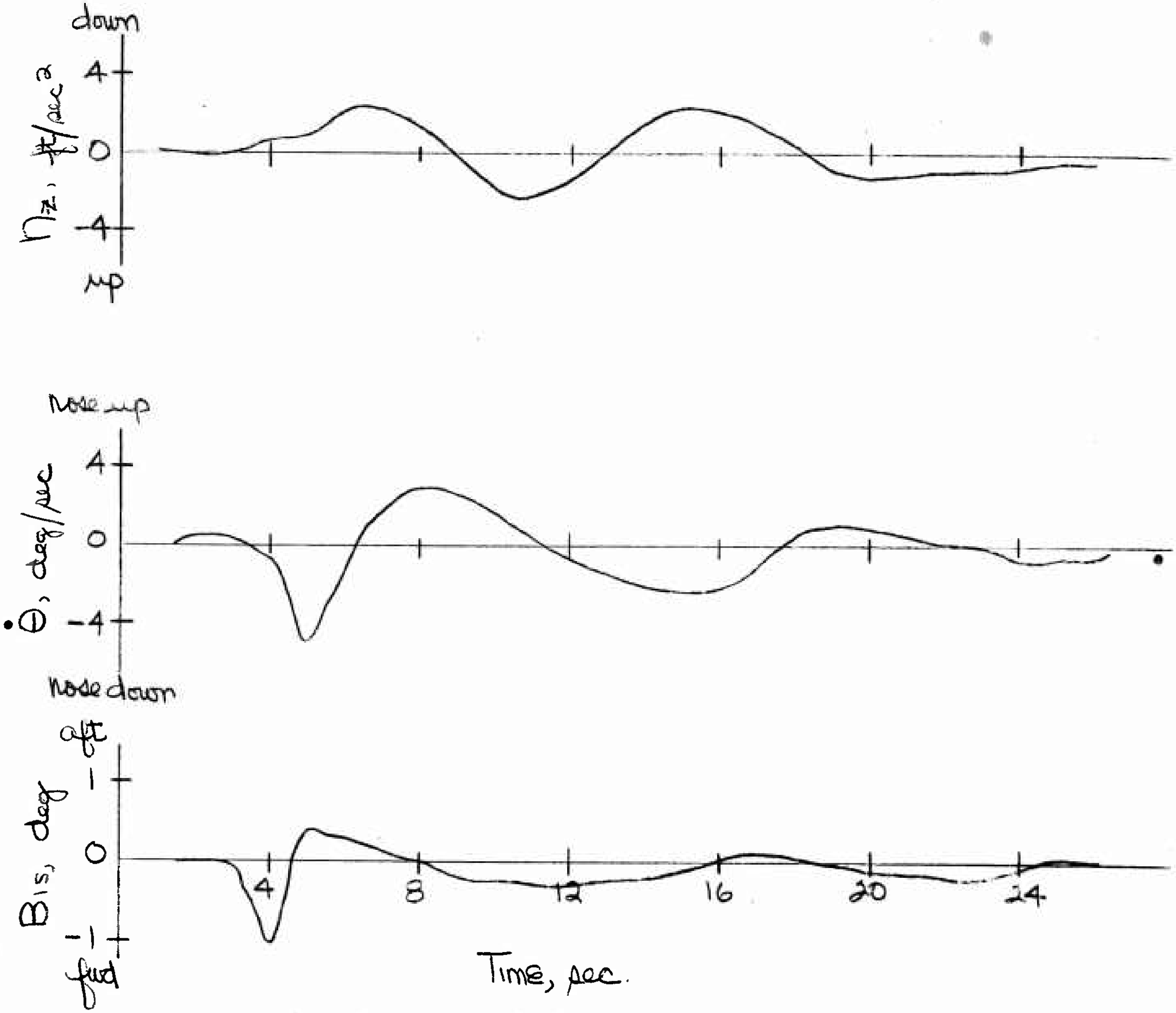

Fig. 4a: H-19D: Full Scale Flight Test Response

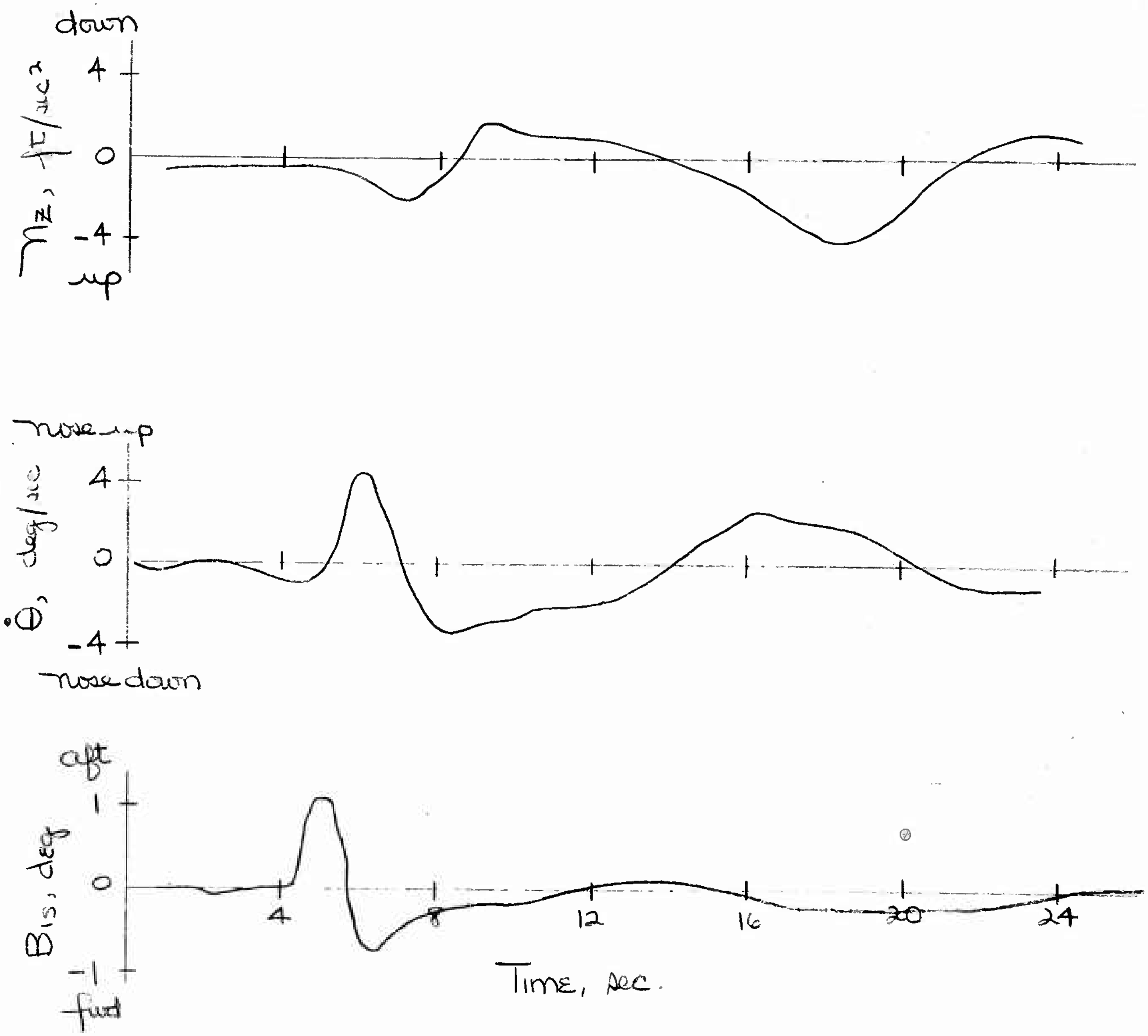

Fig. 4b: H-19D: Full Scale Flight Test Response

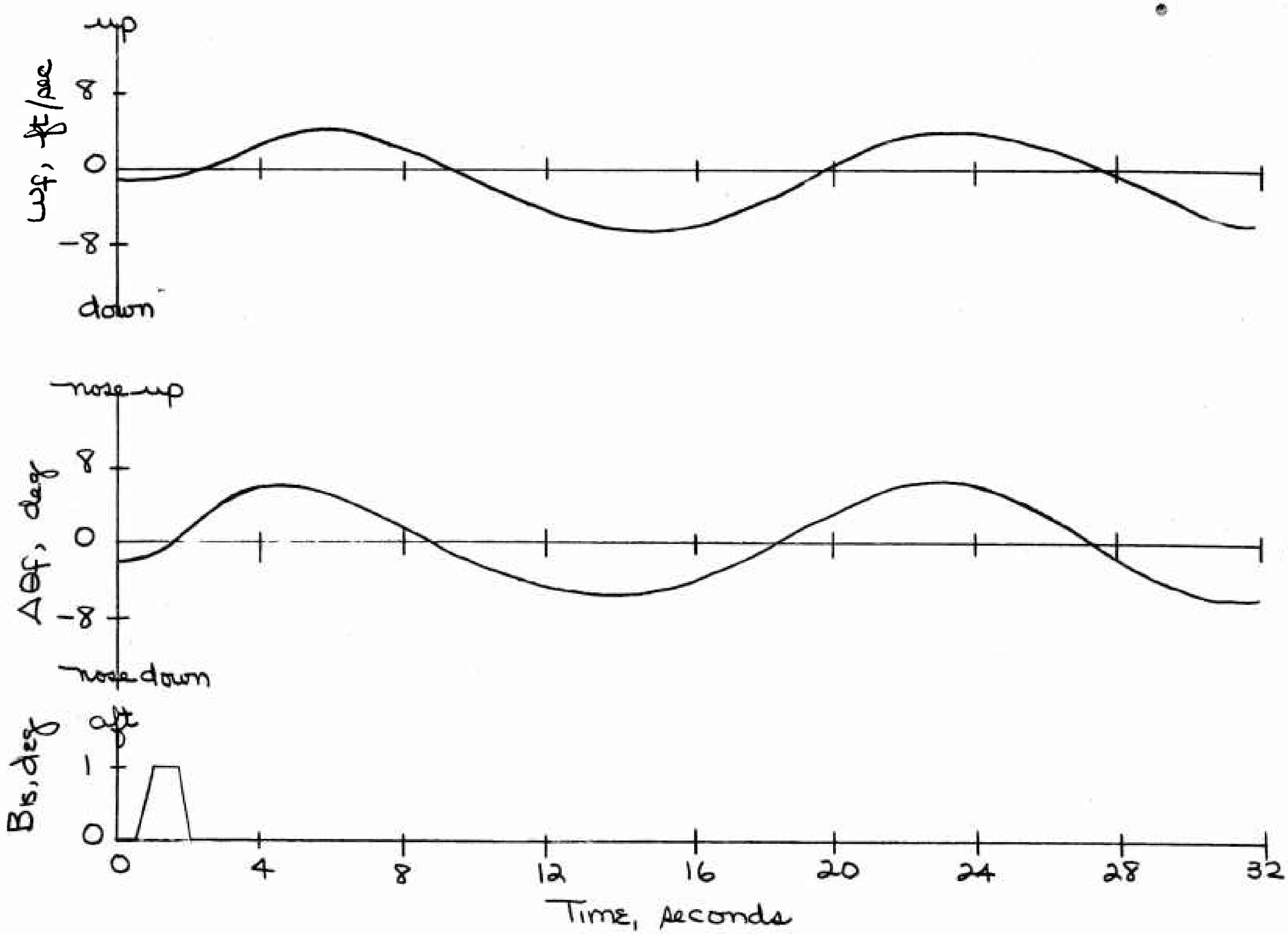

Fig. 5a: H-19D: Model Test Response

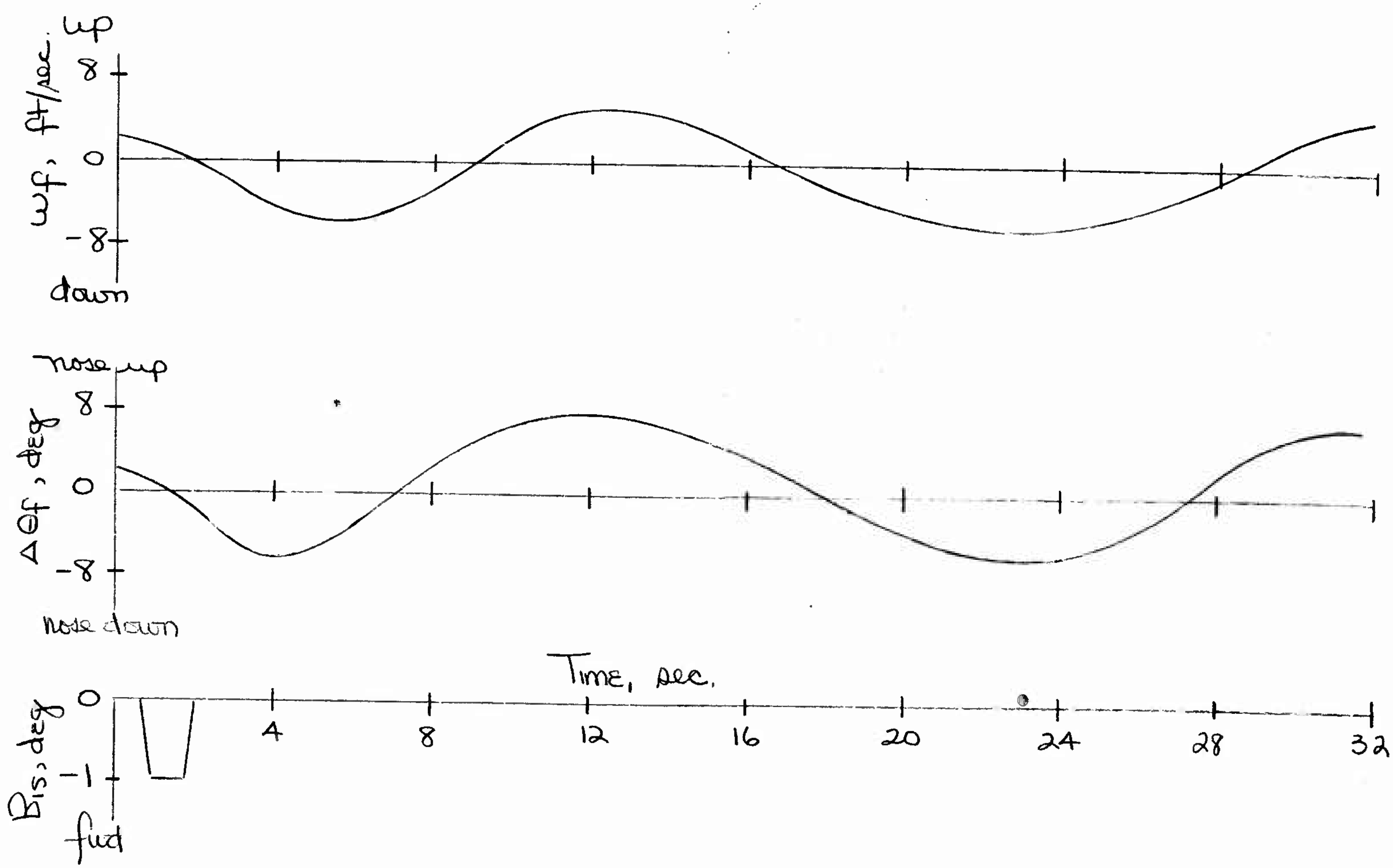

Fig. 5b: H-19D: Model Test Response

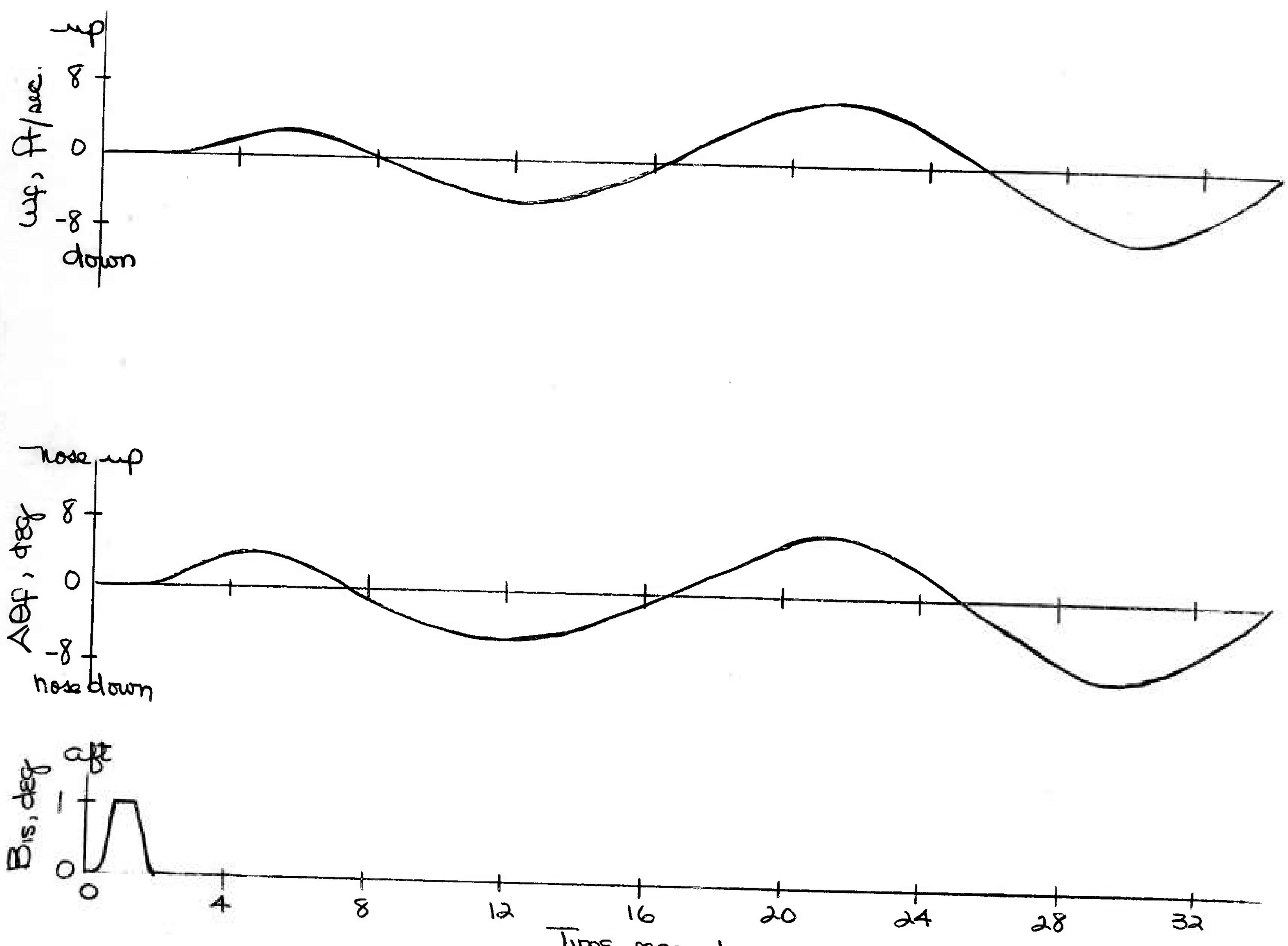

Fig. 6: H-19D: Computed Response to Model Input

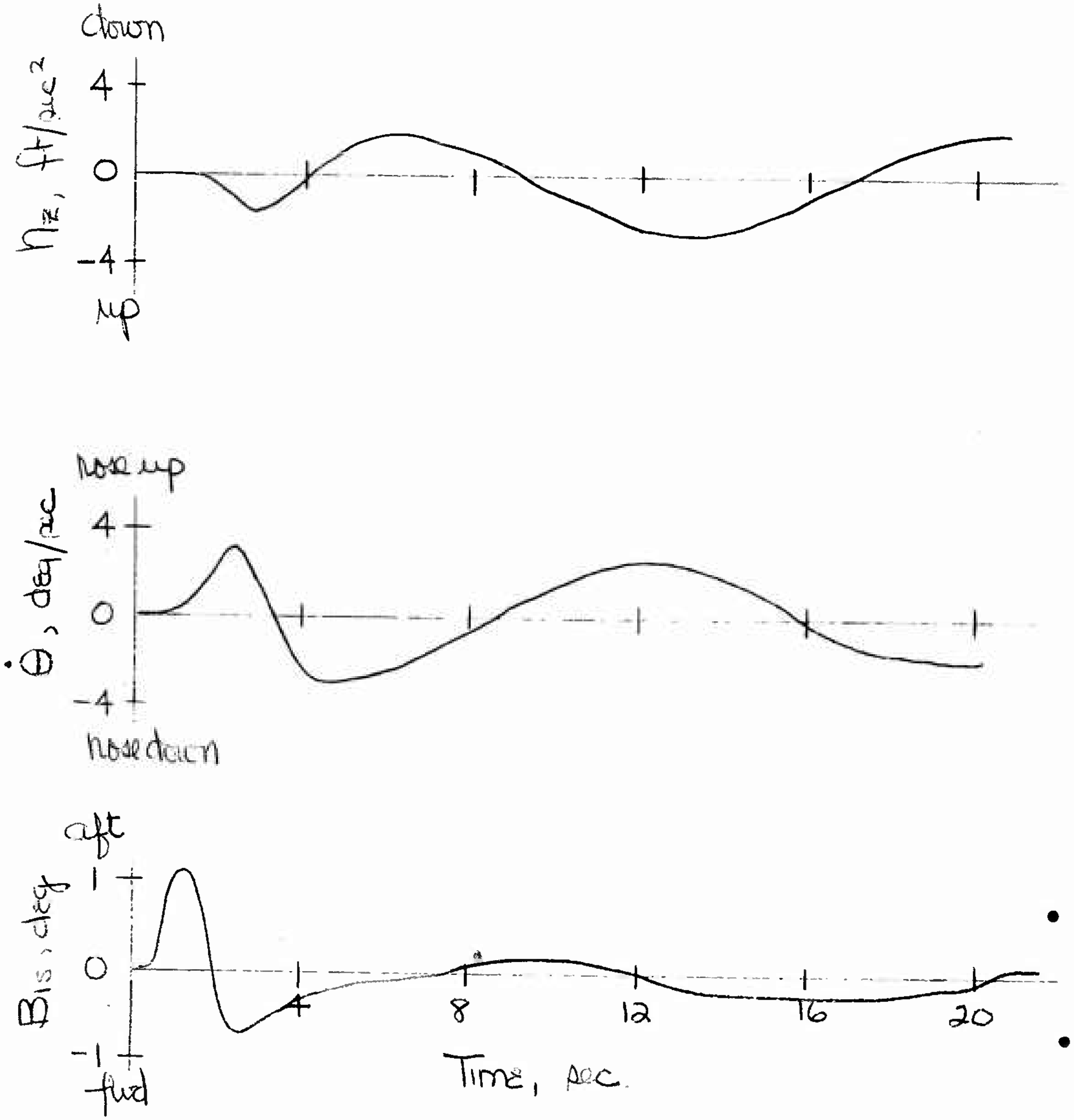

Fig. 7a: H-19D: Computed Response to Flight Test Input

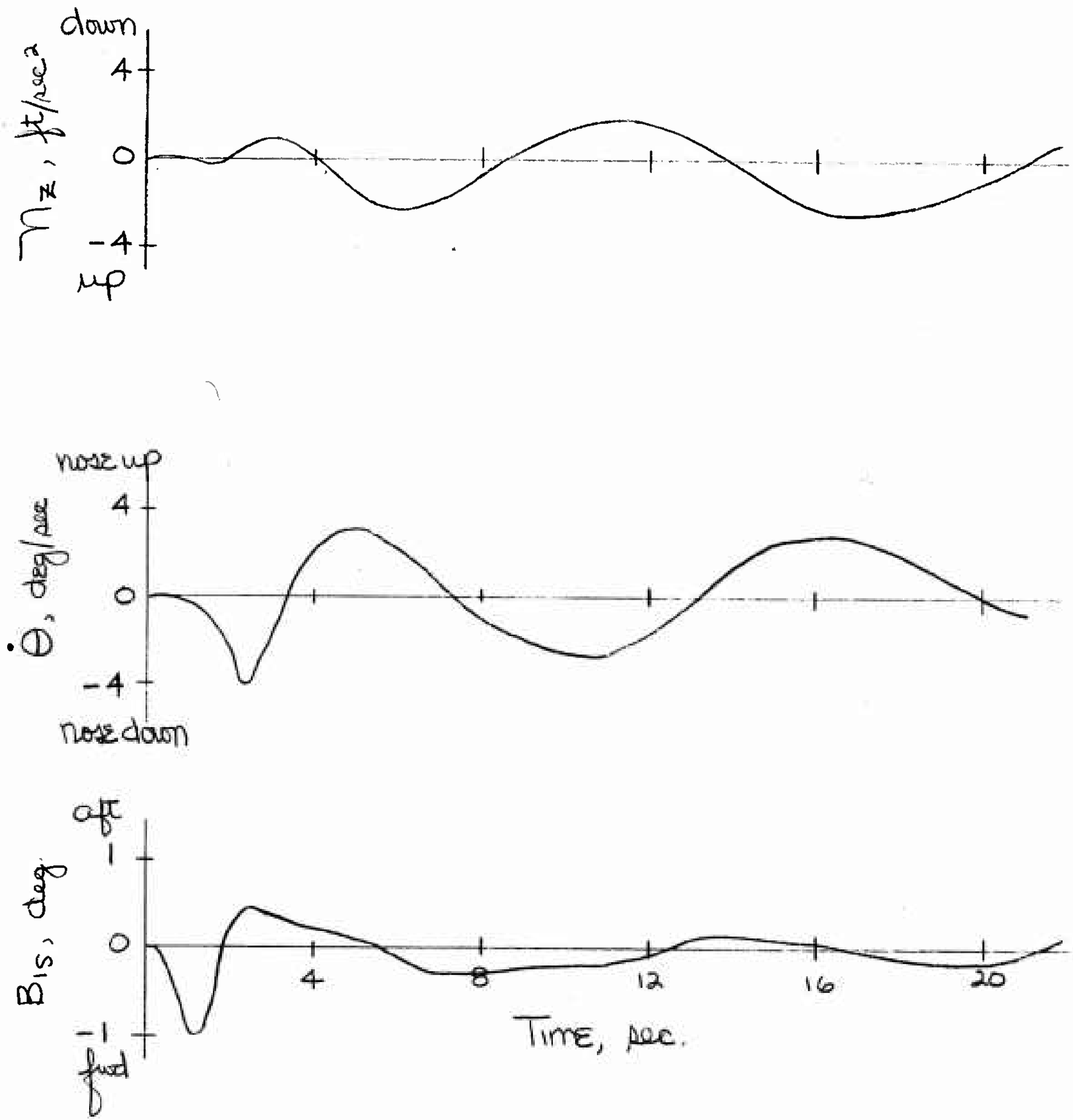

Fig. 7b: H-19D: Computed Response to Flight Test Input

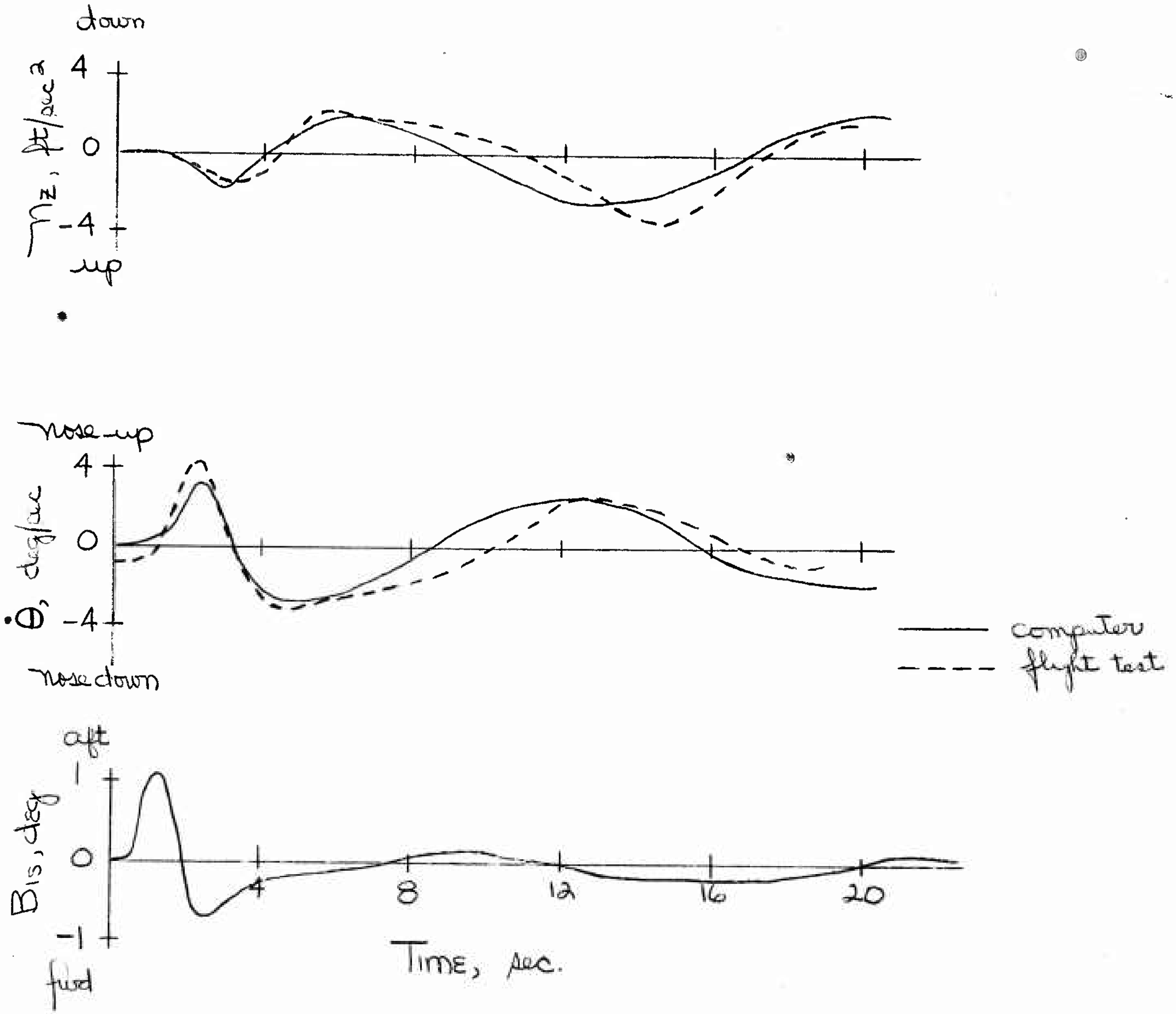

Fig. 8a: H-19D: Comparison of Full Scale and Computed Model Response to Full Scale Input

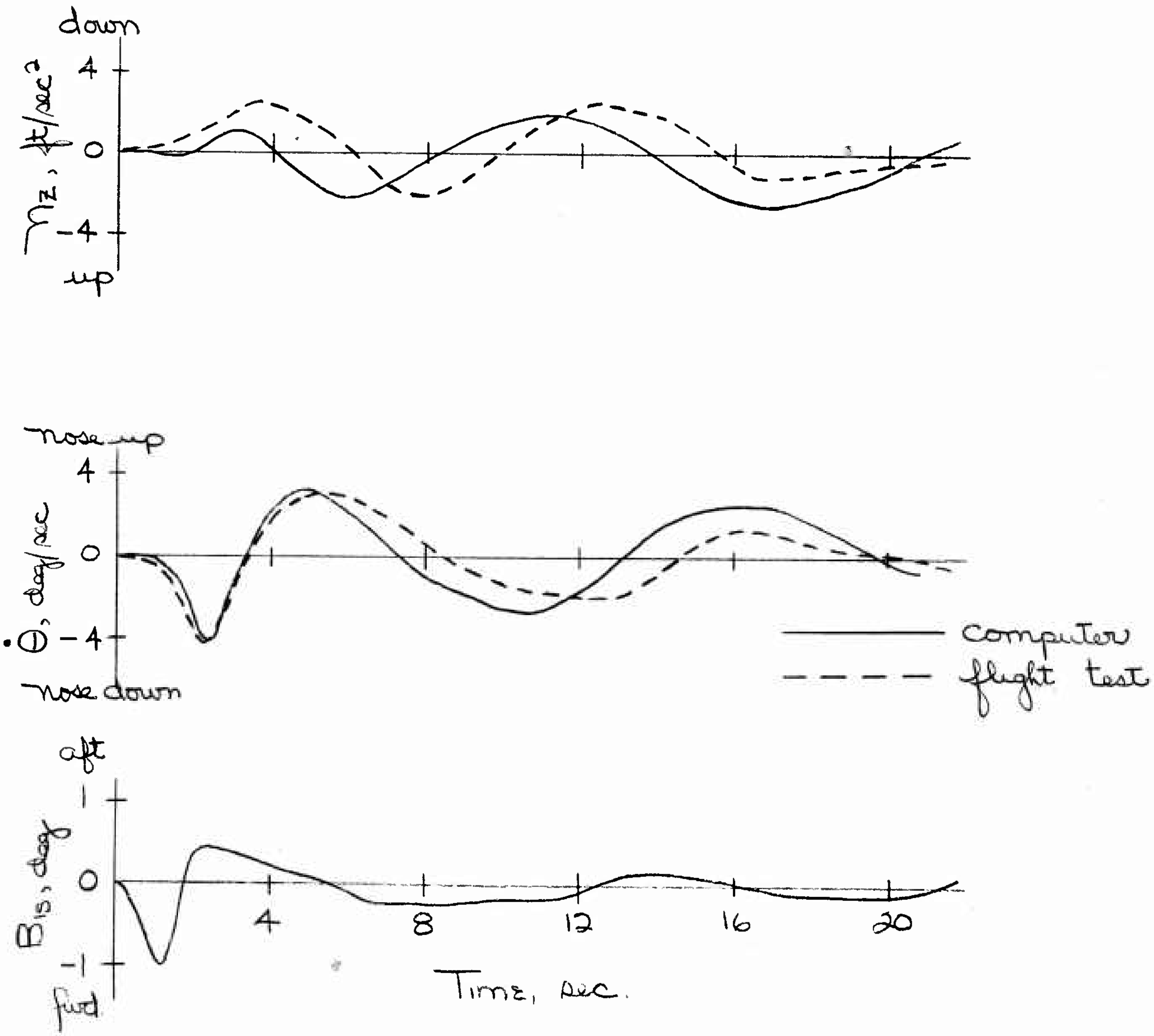

Fig. 8b: H-19D: Comparison of Full Scale and Computed Model Response to Full Scale Input

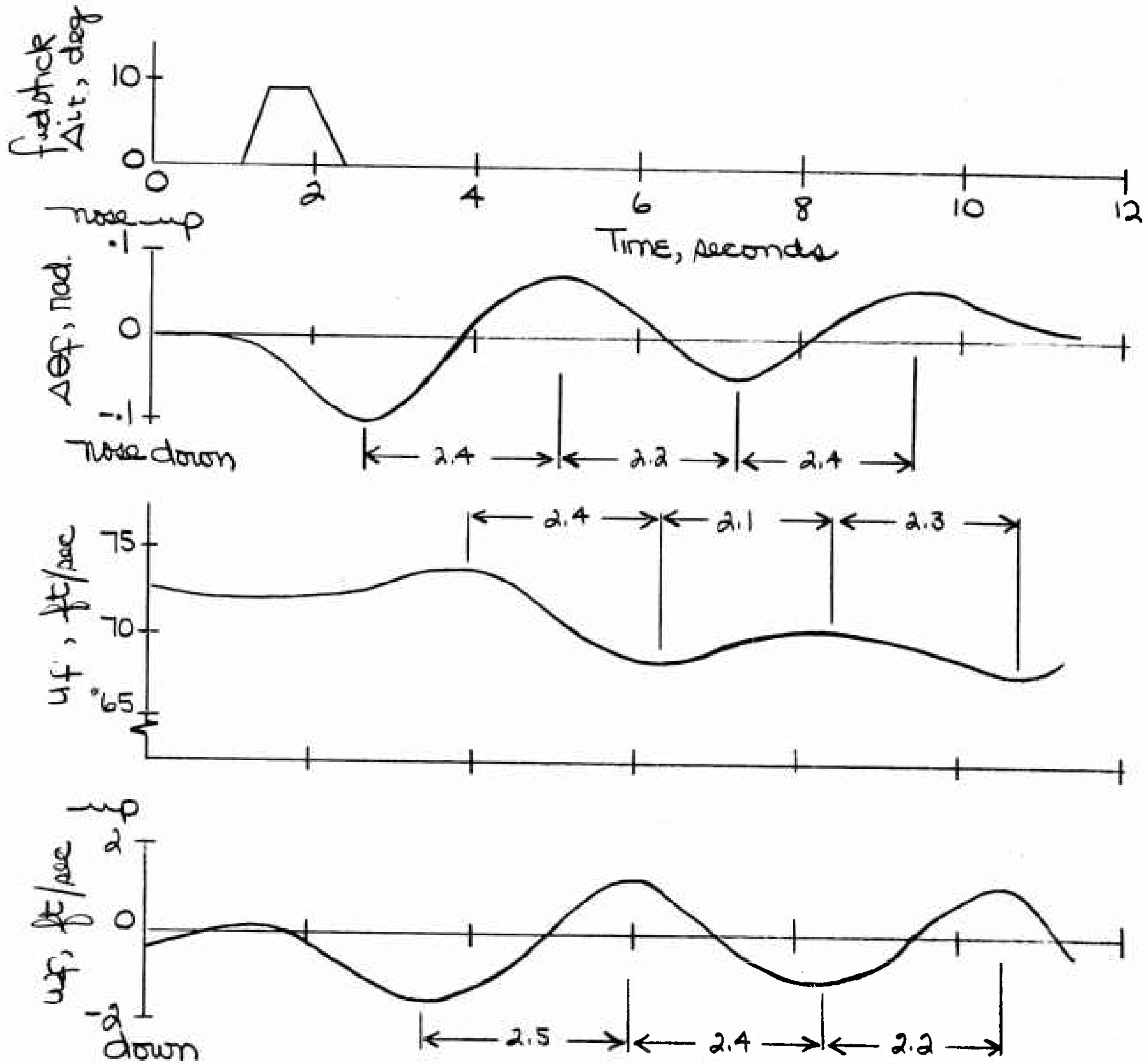

Fig. 9a: V-76: Model Test Response

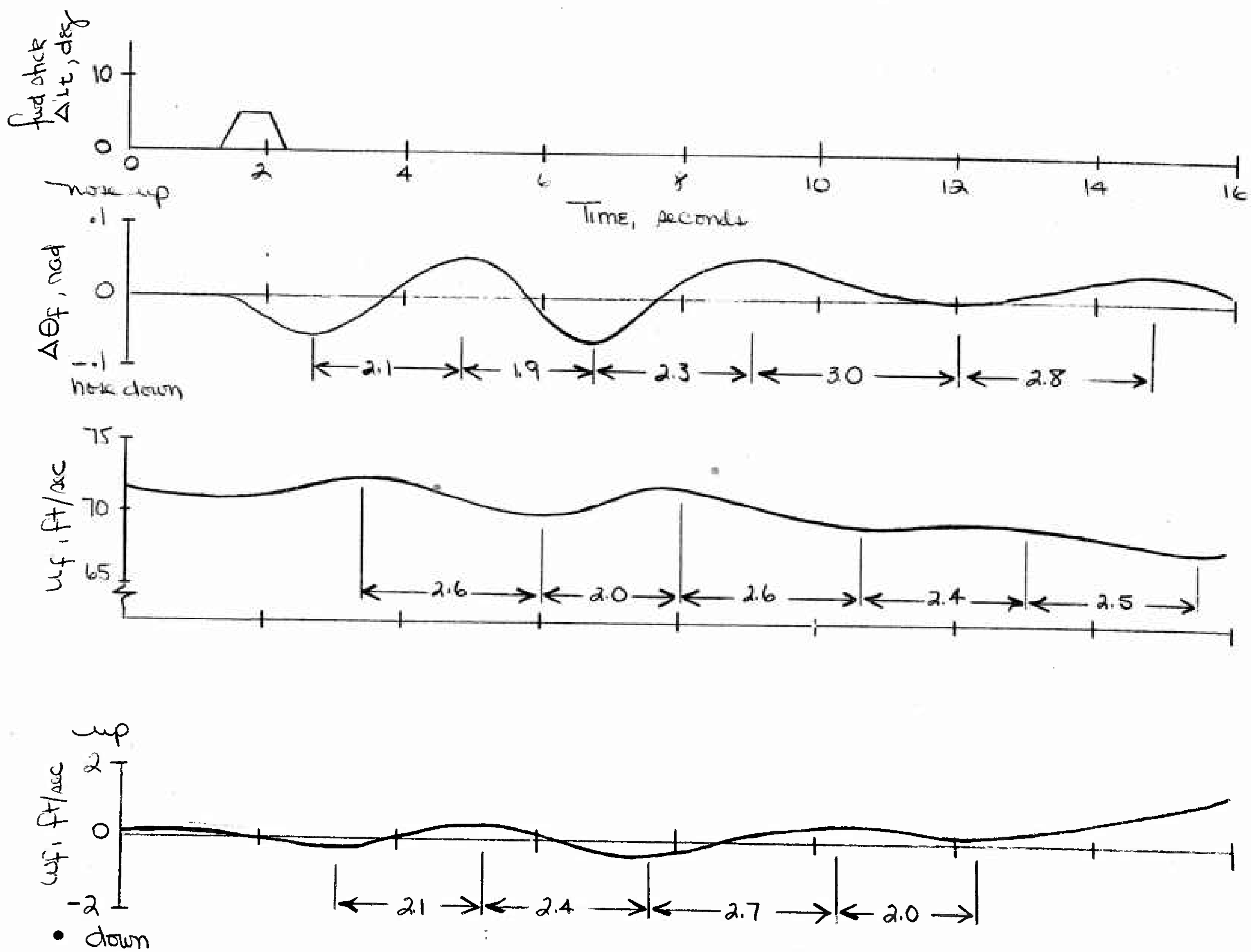

Fig. 9b: V-76: Model Test Response

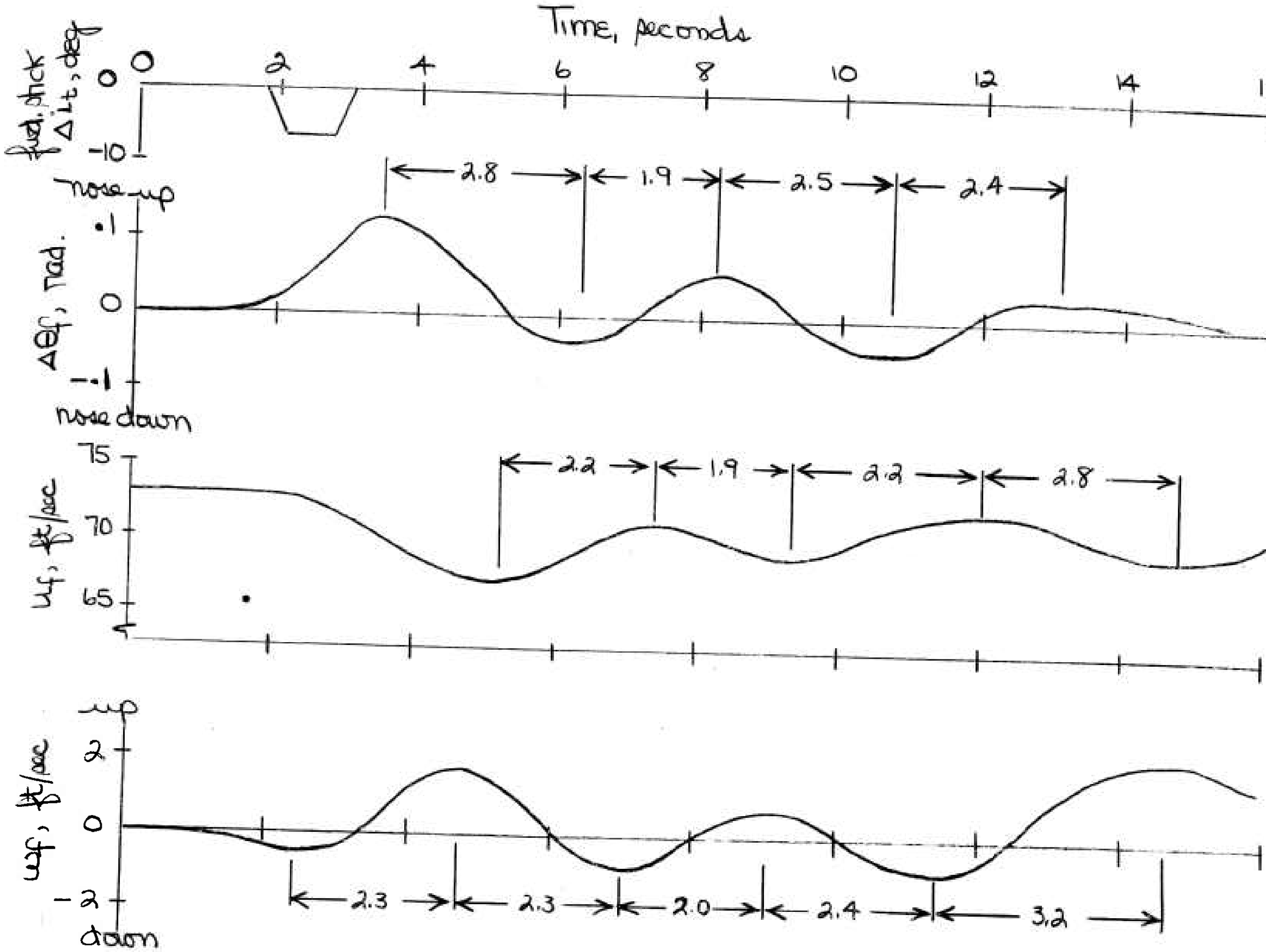

Fig. 9c: V-76: Model Test Response

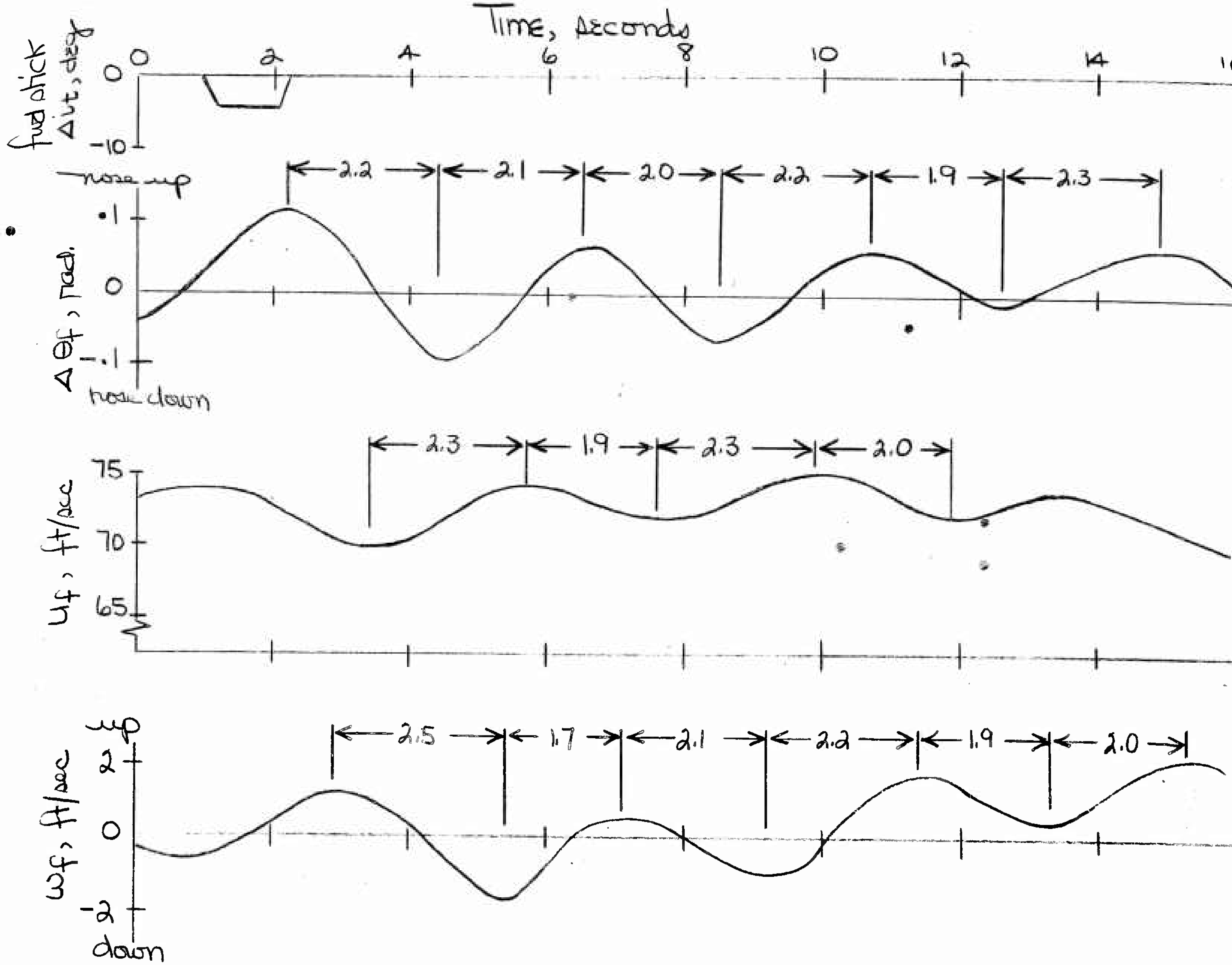

Fig. 9d: V-76: Model Test Response

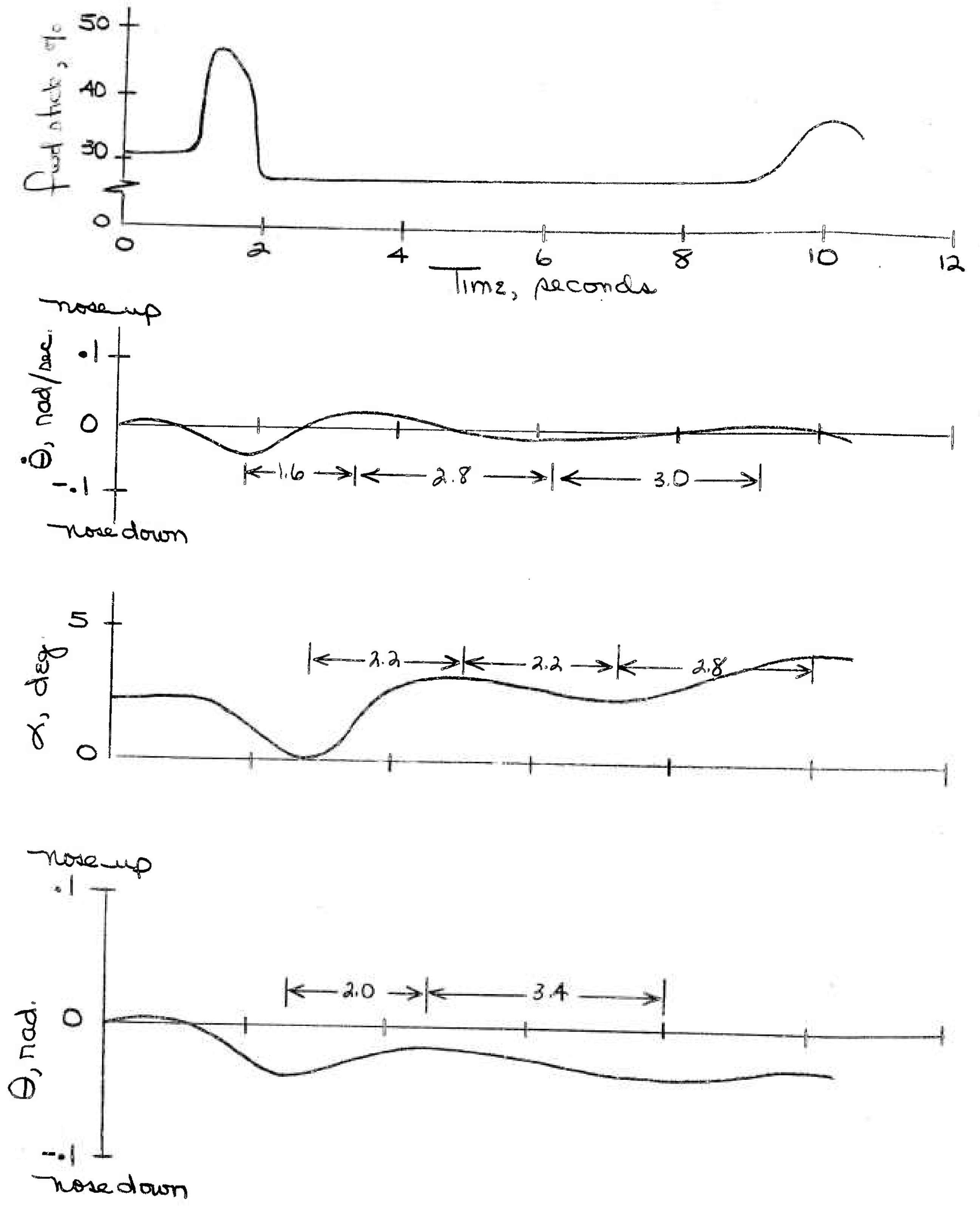

Fig. 10a: V-76: Full Scale Flight Test Response

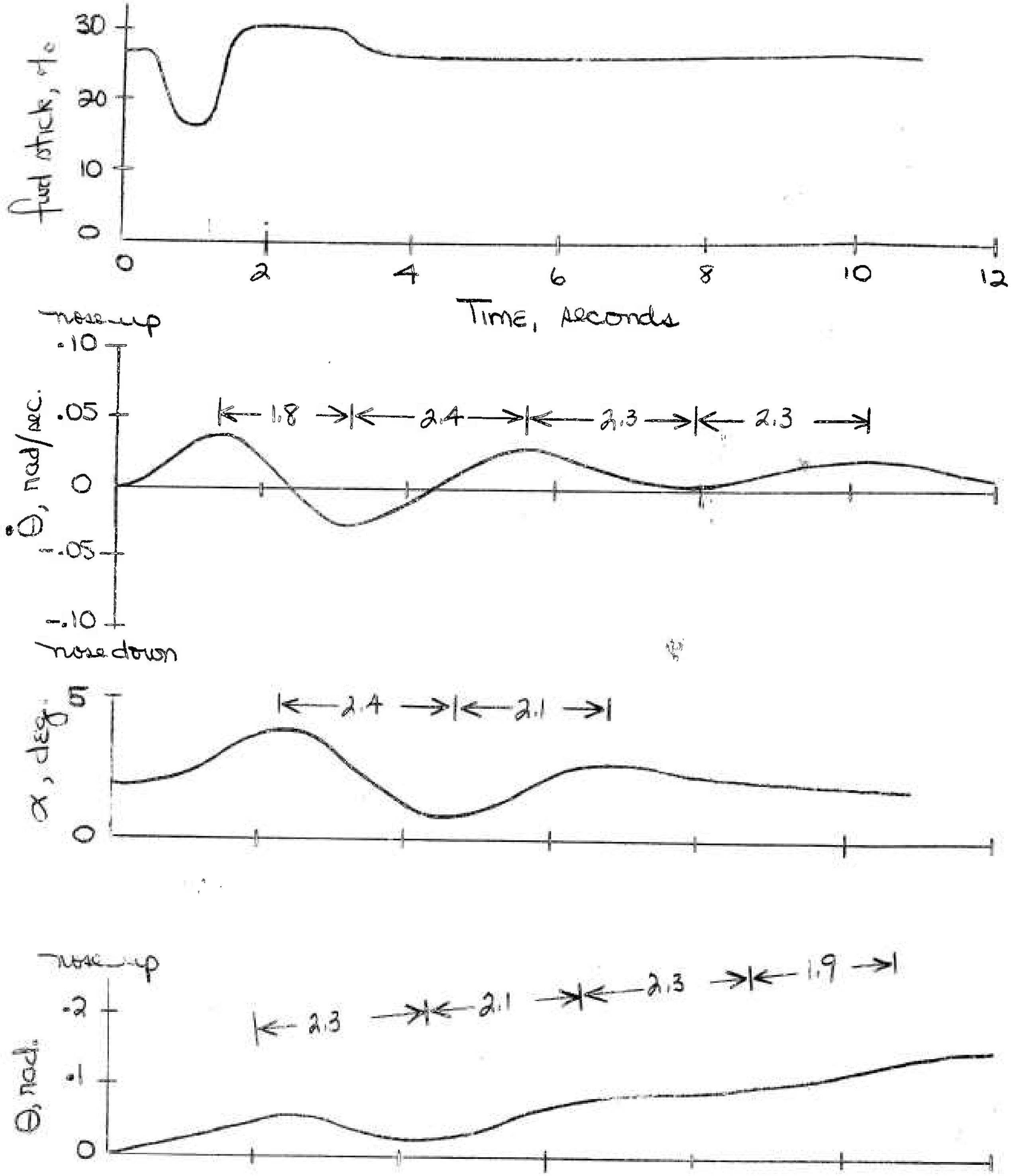

Fig. 10b: V-76: Full Scale Flight Test Response

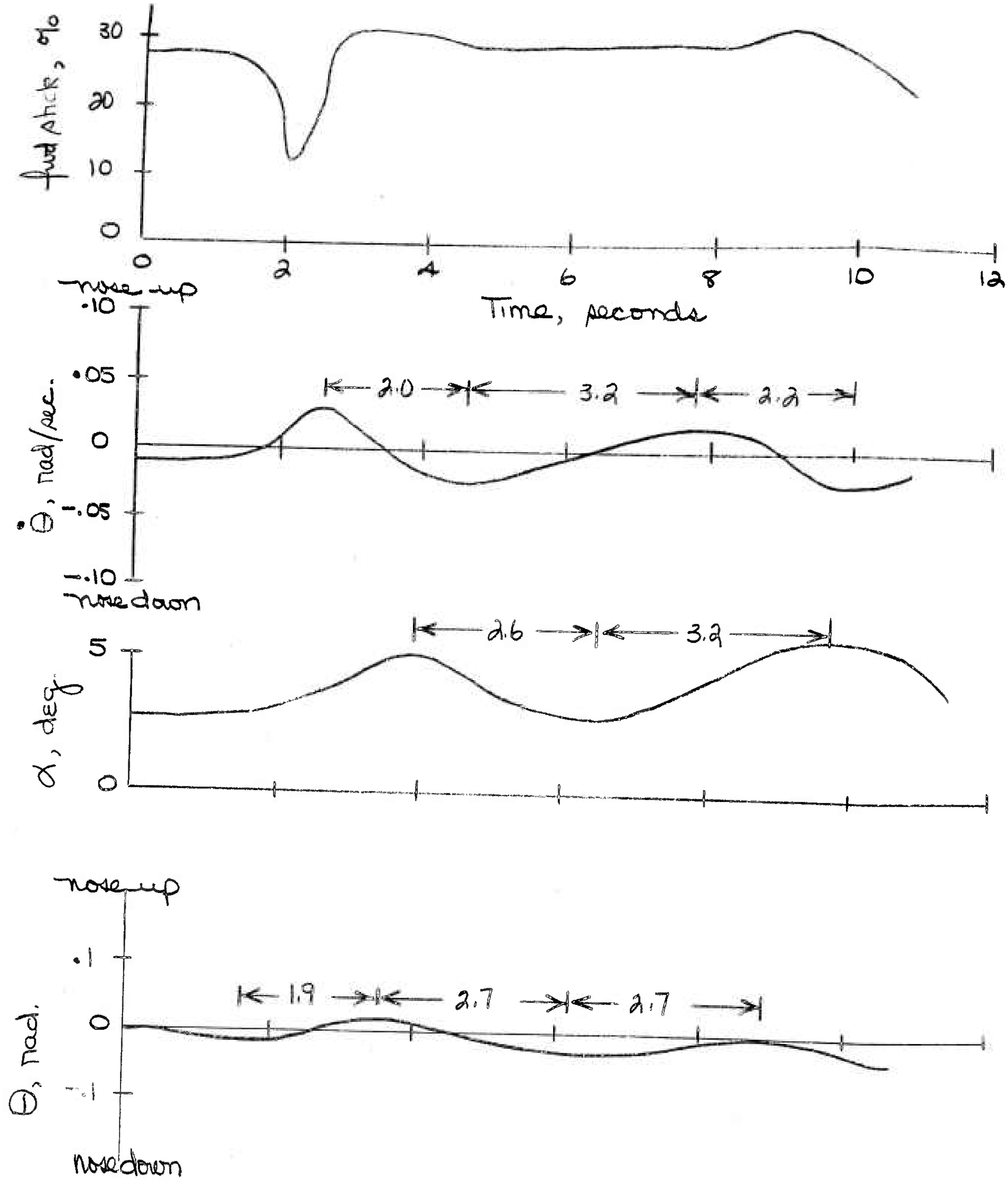

Fig. 10c: V.76: Full Scale Flight Test Response

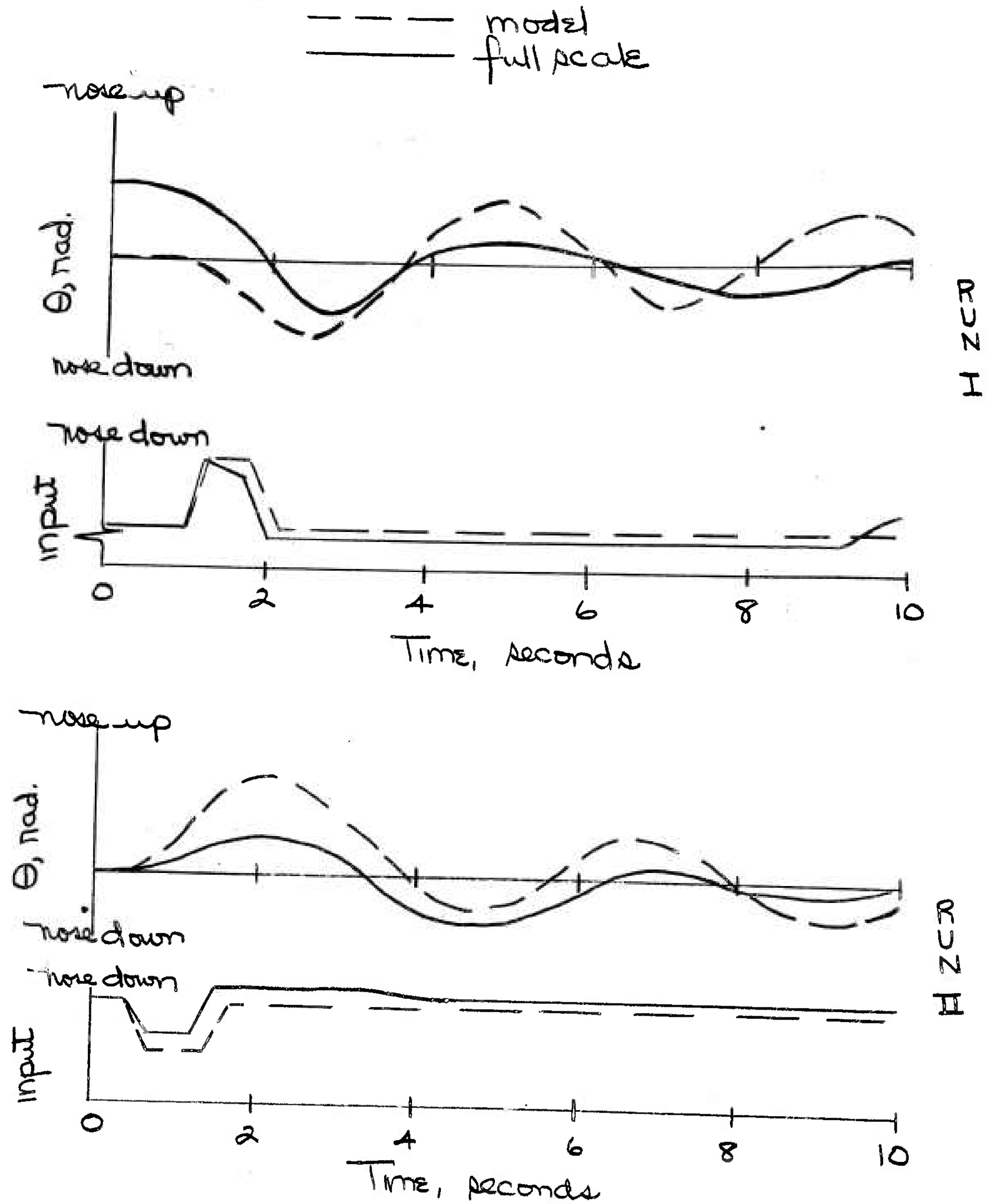

Fig. 11: V-76: Comparison of Full Scale and Model Test Response

Results of experiments to evaluate the degree to which dynamically similar models tested in the Princeton University Forward Flight Facility simulate the dynamics of full scale aircraft are presented.

Two models were utilized, a single rotor helicopter and a tilt-wing VTOL aircraft. Excellent agreement between the response of the models and the full scale aircraft was obtained.

Results of experiments to evaluate the degree to which dynamically similar models tested in the Princeton University Forward Flight Facility simulate the dynamics of a full scale aircraft are presented.

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